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Stabilising textile preforms by means of liquid resin print: a feasibility study

STABILISING TEXTILE PREFORMS BY MEANS OF LIQUID RESIN PRINT: A FEASIBILITY STUDY

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Abstract

This study demonstrates the feasibility of creating stable, pre-consolidated, yet permeable preforms for Liquid Resin Infusion (LRI) manufacture of composite materials. Whilst being one of the cheapest and simplest methods of composites manufacture, LRI with flexible tooling is known for high risk of dimensional and internal defects due to insufficient consolidation of textile preforms. Achieving the quality of a rigid mould solution, at the cost and simplicity of a flexible mould process, is the principal challenge of the LRI.

The approach presented suggests stabilising a compliant preform through point-wise and highly-controlled integration of a binder, and its consolidation prior to liquid moulding. The printed resin creates a stiff skeleton, securing material for resin infusion and curing. This study explores the feasibility and efficiency of novel binding techniques, and the effects it may have on preform properties. Successful implementation of the concept for a multi-ply woven preform is demonstrated and the concept potential is discussed.

Key-words

Liquid Moulding; Resin Infusion; Additive Manufacturing; 3D Printing; Preform;
Consolidation; Binder

1. Introduction

Textile composites are increasingly used for quality-critical applications. Interest in these materials is primarily driven by the cost of manufacturing. Liquid Resin Infusion (LRI) with flexible tooling can be significantly cheaper than conventional autoclave manufacturing, however, there are a number of barriers to their expansion at the present time. One of the fundamental problems of LRI is the dimensional stability of complex components. Concave corners and junctions tend to be smoothed out, thickness distribution is inhomogeneous in convex corners, component edges drift away from the designed path, and large resin rich zones are formed in under-consolidated zones. In addition, thickness variation can lead to non-uniform resin flow during infusion, and as a result, to impregnation defects such as pores and dry regions. The primary reason for these peculiarities is insufficient tooling constraints.

During LRI processes the consolidation and impregnation stages are coupled. Deformation and movement of a highly compliant textile laminate are typically only restrained by a flexible bag, which pressurises the preform when vacuum (that is used to assist resin flow) is applied.

Atmospheric pressure alone is not sufficient to hold the preform in a fixed position and provide the intended homogeneous thickness distribution across the component. Moreover, resin flow and/or any subtle disturbance of the preform while bagging and handling, results in uncontrolled preform movement that may well lead to a dimensional defect.

In current manufacturing practices the generally accepted solution to the dimensional problem is to use rigid moulds to restrain the preform from all sides. This can be an expensive solution which compromises the potential low cost advantages given by LRI. For example, draping deformations may significantly change local compressibility, and would require redesign of costly tooling [1]. Differences in compressibility may also be observed for preforms of the same nominal areal density but different architecture, such as a woven multi-ply and a 3D braided fabrics [2]. Hence a rigid mould Resin Transfer Moulding (RTM) process, where a tool

geometry is optimised for one preform, may be completely invalid for a preform of the same density but different pattern/structure.

This work explores an alternative to the rigid tooling solution, by creating a stiff and stable preform that is consolidated prior to bagging. If it was possible to fix compaction deformations, then the textile could be shaped locally at critical areas (edges, corners, junctions) using a high pressure compaction tooling. The pre-configured preform could then be impregnated using flexible bagging, but without the risk of disturbing the preform tow architecture and component geometry. The main research question is how to effectively lock the consolidation deformations and modify preforms to:

- (1) Make preforms handleable by binding plies in multi-ply stack, preventing the disintegration of a compliant fabric and loss of scattered/loose yarns/filaments in complex net-shaped systems;
- (2) Control a preforms thickness and fibre volume fraction and reach the compaction levels typical for an autoclave moulding.

The main conceptual challenge of stabilising a preform and freezing-in the consolidation deformations is the delivery and distribution of a binding system into the preform. In order to achieve the stated goals, the binder has to be continuously integrated through the thickness of the dry reinforcement to prevent elastic spring-back upon unloading, and keep the fibres in their required positions.

There is a range of commercially available stabilising systems in the form of powder binders/tackifiers [3, 4, 5, 6], veils [7, 8, 9], or matrix solvable through-thickness reinforcements [10]. Thermosetting or thermoplastic resin particles/fibres are spread over the fabric surface, and a preform is consolidated under pressure and heat. This operation does enhance the stability of the reinforcement, and can also reduce elastic spring-back deformations after pressure is released. To maintain the consolidation deformation, the solid particles of binder need to be dissolved and flow into the bulk reinforcement. At a relatively high fraction of epoxy binder the

spring back can be limited to 5-15% [4]. However, alongside the improvement in stability, the intra-yarn flow is significantly impeded by the shapeless clusters of resin, causing poor wettability and intra-yarn porosity [5]. This discrete binder approach is not well suited to deliver binder into the inner layers of 3D reinforcements. Recently, Thoma et al [11] suggested the idea of chemical-stitching, where resin is deposited into the preform discretely in a regular pattern.

Stitching and tufting are other known routes to stabilise preforms. Solvable or structural yarns are inserted through the thickness to bind the plies mechanically. The through-thickness reinforcement cannot, however, be used to control the thickness of binded preforms. Moreover it distorts the fibres in plane, and creates fibre free spacing causing the occurrence of resin rich zones, and eventually, the deterioration of in-plane composite properties.

As an alternative to the existing methods of stabilising reinforcements, this work tests the feasibility of creating a stiff skeleton with a well-defined geometry in a dry preform. This skeleton would constrain preform movements, simplifying handling of the preform and dictating component thickness. The explored form of binding is a pattern of pins of solidified resin introduced without disruption to the reinforcement geometry – Figure 1. These pins must span through the entire thickness covering inter and intra yarn space, be sufficiently stiff to resist the preform spring-back after consolidation, be local to minimise the disruption of resin flow during infusion, be defect/pore free, and be compatible with a resin used in infusion.

The resin pinning is not considered to be a substitution of conventional binding or stitching processes but aims at point-wise stabilisation of textile preforms in the locations where thickness tolerances are low or risks of defect occurrence are high. Ideally this technique should be compatible with any other binding procedure. Unlike powder binding technique used for overall shape control, the primary role of resin pinning is to enhance (structurally and dimensionally) critical areas – edges, junctions, high curvature radii, corners, etc, or to create a solid carcass restraining the preform movements.

The introduction of these pins is the main process in question for the paper. The resin has to be delivered in a liquid state, however, it cannot simply be poured onto a fabric surface. Due to capillary forces within yarns and open spaces in-between plies, a liquid tends to spread over in the surface plies and does not penetrate a stack deep enough unless an excessive volume of resin is applied. The presented concept is to apply the resin through precise point-wise injections building up pins additively through the thickness of the reinforcement. Once preform is uniformly saturated with liquid binder in a required location the pin is cured assisted by heat and pressure.

The paper addresses the questions of resin delivery, pin size/shape control, and the distribution of consolidating material. Thus, the major aims include:

- (1) To explore *feasibility of liquid resin printing* – a novel rig implementing the precise and programmed introduction of the resin is presented. The feasibility of high precision injections with fluid of various viscosities and constraints are discussed along with the features of consolidated material;
- (2) To demonstrate the opportunity of *stabilising multi-ply preforms* and by doing that to attempt increasing the quality of liquid moulded components produced by a simpler and cheaper manufacturing technique;
- (3) To study the impact of *resin pinning on the LRI*. The feasibility of resin infusion and the challenges associated with impregnating pre-consolidated preforms are discussed.

2. Experimental set-up

2.1 Liquid resin printer

In order to implement the concept of resin pinning, an automated injection rig was designed and built through modification to an existing 3D printing system, the RepRap Mendel. As an open source venture, the RepRap hardware and firmware provided flexibility in altering the machine for this purpose. The most substantial of these modifications was the replacement of the standard RepRap thermoplastic extrusion head with a simple syringe pump arrangement

(accommodating 10ml Luer Lock BD Plastipak syringes) – Figure 2. The injection rig has three degrees of freedom (parallel translation in x,y,z directions) and independent control over the injection volumes. The set-up is automated and allows for the application of various injection patterns both in-plane and through-thickness of a preform. The Mendel's accuracy in Cartesian movements is 0.1mm and trials demonstrated the syringe pump to be accurate to 1 µl (as measured by weight in a 1000µl dose). To promote through-thickness flow and control the pin dimensions better, preforms needed to be constrained. 10 mm thick preform holders were manufactured from Perspex and bolted to the base plate of the injection rig. The syringe needle is inserted through holes in the constraining plates. In this study, needles with a diameter of 260 µm was used.

2.2 Materials

Balanced multi-ply preforms, based on HS carbon fibre 5-harness satin (Hexcel G0803/G0963) with an areal density of 285 g/m² per ply, was used. The fabric was woven of 3K yarns (linear density 203 tex), and had a yarn spacing of 1.38 mm (ends/picks count of 7.2 yarn/cm).

Conventional resin systems designed for LRI were used both for pinning and infusion. Interest in a standard LRI resin was due to its known flow, curing, and binding characteristics. A pin made of such a resin would be chemically identical to the rest of the composite, minimising the disruption and stiffness contrast caused by its presence in the composite. In principle, any injectable resin system can be used for pinning. Moreover, this procedure could be used to enhance properties or functionalize the composite at the same time.

Prime 20LV low-viscosity low-exotherm transparent epoxy was used as a benchmark liquid resin as it was specifically designed for LRI, including the flexible tooling process. The resin can be cured at range of temperatures and curing times. The variant used in this study was the extra slow hardener, cured for 6 hours at 65°C according to the manufacturer's specification.

3. Liquid resin print

3.1 Feasibility of high precision injections

Injection experiments were conducted on a 16-ply 5HS preform housed in the Perspex rig containing a 90 x 90 x 10mm cavity to accommodate the preform stack and a 9x9 injection hole array (10 mm spacing). Perspex as the choice of tooling material (with Nylon screws) provided both visual transparency and radiolucency to allow for observation of the resin flow using X-Ray tomography (CT-Scan). Preforms were wrapped in an envelope of PTFE release film. The frame held the plies together during injection and examination, but did not impose significant compaction pressure – the average fibre volume fraction was 26.4% (corresponding to an average ply thickness of 0.65 mm).

To visualise the flow of injected resin and study the fluid distribution, dye penetrant fluids were chosen. Zinc dioxide (ZnO_2) powder with particle size not exceeding 5 μm , which can be detected by X-Rays, was dispersed in two carriers of propanol (viscosity ~ 2 cP) and Prime 20LV epoxy (~ 600 cP). Propanol does not represent any commercial resin but was used to demonstrate the extreme example of flow and fluid distributions if lower viscosity systems are to be used. The injections were applied at various depths and volumes - Figure 3a. At each in-plane location of needle insertion there was either a single injection or several injections at different depths. The following programme, as shown on Figure 3b, was implemented: (I) three injections per thickness in a column with various injection volumes; (II) single injections of different volumes at the same depth; (III) single injections of the same volume at different depths. Fluids were injected at the rate of 8 ml/min.

The experiments demonstrated the ability of the set-up to deliver a required binder volume to any location in a textile preform. It also revealed important flow features:

- (a) The injected fluid remained in the local vicinity of the injection site and tended to spread in-plane of the preform rather than through thickness;

(b) Zn particle position was confined to within a few plies around the needle tip. As the volume of injections increased it led to a further spreading of the liquid in the plane of fabric;

(c) The thickness of the impregnated layer was comparable to the size of the needles taper of ~3mm.

The flow patterns of the considered fluids, revealed by X-Ray examination, appeared to be pronouncedly different. Epoxy clusters were more local, with their maximum in-plane size almost linearly proportional to the quantity of injected material. It evolved from 4 to 8 mm with the injection volume increasing from 8 to 16 μl – Figure 3c. In the case of the low viscosity fluid the maximum linear dimensions of the clusters exceeded 15 mm even for the smallest injected quantity – Figure 3b. The increase in the injection volume resulted in the thickness growth of the zinc cluster from 2.6 to 3.4 mm for the propanol solution and from ~1.7 to ~2.0/2.5 mm for the epoxy. Hence, the preform volume affected by the fluid appears to be smaller, both in-plane and through-thickness, for the fluid with higher viscosity.

The wetted area can be estimated for two flow scenarios: (a) the entire volume of fluid is held within the yarns and (b) the fluid propagates uniformly in the inter- and intra-yarn space. The required inter-yarn porosity (20.0%) and the intra-yarn fibre volume fraction (33.1%) for these estimates were obtained based on the known average ply thickness and weave density. If the fluid is spread uniformly throughout the volume, then for the given geometry, the diameter of a circle area affected by 8 μl injection is estimated to be 4.6 mm if two plies are impregnated or 5.3 mm if resin spreads over three plies. If the resin is pulled into the yarns and the intra-yarn space remains unaffected, the dimensions should increase to 9.3 mm for two plies and 11.5 mm for three plies. Comparison of the obtained values with the cluster dimensions seen in the experiments implied that the major fraction of the viscous resin was accumulated in the inter-ply and intra-yarn spaces; whereas capillary forces dragged the entire volume of a thin fluid into the yarns and possibly not even fully impregnating them in the affected area. This suggests that

resins systems with a very low viscosity may not be appropriate for the purposes of resin pinning. The absence of resin in inter-yarn spaces leads to the occurrence of porous pins.

These trials are in agreement with the analysis of traditional non-vacuum assisted RTM. As shown for various architectures [12, 13, 14], there exists an optimum balance of injection speed, resin viscosity, resin surface tension, and fibre-matrix contact angle at which the flow propagates uniformly in the inter- and intra-yarn space. Patel et al [12] introduced a modified Capillary number, which condenses all of these characteristics into one dimensionless parameter, and dictates the void volume fraction. The experiments with propanol solution confirmed that capillary forces dominate when the resin viscosity is too low.

The CT scans demonstrated that in contrast to conventional stitching, fabric disruption caused by needle insertion was negligible compared to the characteristic features of the weave. The needle did leave a visible trace ($\sim 100\text{--}300\text{ }\mu\text{m}$ in diameter), however, aside from the point of piercing the structure seemingly remains unaffected.

3.2 Feasibility of consolidation

Consolidation tests with a reactive resin were conducted using different injection volumes (ranging from 8 to 40 μl per injection) and patterns. The settings for the injections were kept similar to the injection trials described previously except that the number of plies was increased to 24 to reduce or close the channels for intra-yarn flow. The fibre volume fraction during injection was thus raised to $\sim 40\%$. The number of injection steps in a column was also increased to a minimum 7 per thickness of preform, in order to have at least one injection per three plies. After injection, preforms were consolidated in a hot press at pressures exceeding 0.6 MPa and temperatures corresponding to the cure program of the utilised epoxy.

Pins were found to have a well-defined geometries on the textile surface, spanned through thickness, and the consolidation deformations held in the fabric approached 65% fibre volume fraction at the pin centre (estimated based on the known areal density of fabric, density of carbon fibres, and preform thickness). The non-impregnated areas of the preform sprung back

1 elastically after consolidation, which created a substantial thickness variation of ~10% between
2 the pinned and dry area, Figure 4. The thickness of the dry areas between pins aligned with the
3 fibre direction found to be substantially smaller compared to the pins placed at 45° to the fibre
4 direction. It is suggested that the yarns bridging the pins retained the dry area in between them,
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6 resisting elastic thickness recovery on unloading.
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10 CT scan shows pins to be barrel in shape, being wider in the bulk of the preform. The preform
11 was impregnated uniformly throughout the thickness except for the bottom ply. This was due to
12 significant tapering (~3 mm long) of the needle, meaning it could not be inserted as deep as
13 required to fully impregnate the bottom plies. In subsequent process optimisation trials it was
14 shown that this issue can be corrected by increasing the volume of the injection in the bottom
15 ply.
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25 The surface analysis of the pinned preforms showed a noticeable widening of yarns at the
26 consolidated regions compared to the dry areas – Figure 5. It was estimated that the average
27 yarn width increased by 20-25%. In the pins, yarns clearly exceeded the yarn spacing of
28 ~1.4 mm, which led to the yarn jamming and the overlap effect known for other woven fabrics
29 [1]. This feature has a significant impact on fabric compressibility and through-thickness
30 permeability.
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40 Various patterns and injection volumes were implemented for demonstration purposes and
41 Figure 6 shows examples of pinned preforms consolidated in different ways. It can be seen that
42 overall a good control of pin position and dimensions is achieved. Depending on the
43 manufacturing requirements, pin density and size can either be minimised to enhance resin flow
44 during the infusion, or maximised to reduce thickness variation, and improve preform stability.
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51 Figure 6b shows an example of a pinned $[0^\circ, 45^\circ]_s$ stack. Waviness in this preform was
52 significantly reduced compared to the 0° stacked samples. The minor thickness variation
53 between bridged pins was owed due to fibre crimp. Yarn crimp (1.4% for the 5HS fabric)
54 allowed for a certain thickness recovery at the expense of straightening fibres. Hence spring
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back effects can be minimised, or fully eliminated, by creating quasi-isotropic laminates or bridging the pins on the surface by layers of non-crimp fabric.

Samples for LRI trials were produced as 300×90 mm preforms with different lay-ups and pin patterns tailored for the need of LRI (discussed below) – Figure 7. Consolidation was deemed satisfactory – uniform cured pins of approximately 10 mm in diameter were clearly separated by dry channels, leaving space for the resin flow during infusion.

4. Liquid moulding of pre-consolidated preforms

Infusion trials were primarily targeted at establishing whether the pinning process used and increase in fibre volume fraction lead to the occurrence of any significant defects. The major concerns were:

- (a) Consolidation inevitably leads to a significant drop in preform permeability. The Kozeny-Carman model predicts a reduction of in-plane permeability by a factor of ~ 9 as the fibre volume fraction grows from 50 to 70%. The impact of consolidation on through-thickness permeability can be even stronger, and reach two orders of magnitude for the same range of fibre volume fractions [15, 16, 17, 18]. The decrease in permeability impacts on infusion time and elevates risks of poor impregnation. Some variants of LRI are specifically designed to increase permeability by either releasing the pressure imposed by the bagging film, as suggested in Vacuum Induced Preform Relaxation (VIPR) [19], or by modifying preforms, as suggested by Pearce et al [20]. However, pre-consolidation makes it impossible to follow these routes.
- (b) Compaction affects the ratio of in-plane to out-of plane permeability. This increases the risk of forming surface defects due to preferential flow in the plane of the preform. As was shown in Figure 5, yarn cross-overs in the pins are densely packed, leaving no free channels for through-thickness flow. In this state the preform permeability will not exceed the low transverse permeability of unidirectional fibre bundles. Hence upon compaction through-thickness permeability is decreased faster than the in-plane. Many LRI methods rely on through-thickness flow, as implemented in Seemann's (SCRIMP) process by means of a highly permeable

distribution media [21], channels engraved in a constraining rigid plate [22] or in the core of sandwich panels [23]. It is thus important to check the feasibility of flow through the preform thickness;

(c) Stiff pins present obstacles for in-plane flow, which may lead to the possible formation of dry areas in close proximity to them;

Along with these negative factors, an optimised design of the pin pattern can be used to address the issues of permeability and flow control. For example, the diagonal pin pattern in Figure 7a is oriented at 45° to the warp direction, which may help to address the issue of increased ratio of in-plane to through-thickness permeability. The resultant inter-pin channels (~8 mm wide) were oriented at an angle to the fibre direction. Since the permeability in the bias direction is lower compared to the fibre direction, this pin arrangement allowed slowing of the in-plane resin flow without further affecting the inter-ply impregnation. Figure 7b presents an even more radical solution, where in-plane flow along the panel axis was fully blocked. Pin dams divided the panel into isolated segments, forcing the resin to flow in only one direction – through thickness – thus eliminating the issue with the resin flow front formation.

End-to-end infusion experiments along the preform length were conducted using a variation of the conventional LRI scheme. It utilised a single vacuum bag with a resin distribution mesh placed at the preform surfaces. Six layers of low density knitted polyester mesh at the bottom surface and two layers at the top surface, separated from the preform by peel ply (Tygavac polyester peel ply with areal density of 95 g/m²), were used. This mesh was applied to promote the accumulation of the resin at the surface, and to assist out-of plane impregnation concurrently to the in-plane flow – Figure 8. The process was divided into two stages:

- (1) Under application of a low vacuum (60 kPa) the resin was driven into the thick permeable mesh placed underneath the preform to the vacuum port 1 (used as a sensor of mesh filling);
- (2) As soon as the resin impregnated the bottom mesh, port 1 was closed, the vacuum level was increased to maximum, and port two above the composite surface was opened.

In general, the infusion runs were realised in accordance to the designed scheme. The first stage took 50 minutes for the resin to impregnate the mesh under the given conditions. Upon applying the full vacuum, it took another 30 minutes for the resin to cover the mesh/breather on top of the preform and to reach port 2. The major fraction of time was taken by filling of the thick resin distribution mesh. Mesh filling was independent of the preform consolidation and in one form or another is realised in all infusion processes. Optimising the mesh or utilising Fast Remotely Actuated Channels (FASTRAC) processes [24, 25], Floor Flooding Chamber (FFC) method [26], or SCRIMP processes [21] may improve this aspect of the infusion process used.

Resin infusion optimisation goes beyond the scope of the current paper, however, to demonstrate the potential scope for processing pre-consolidated panels, alternative infusion tests were conducted. In those tests the bottom distribution mesh was substituted with a foam block (Syrofoam HD300) containing carved-in channels (10 mm in depth and width) of one central channel along the panel length and 7 equally spaced channels along the width. This modification decreased the total filling time by a factor of 10. The pins were demonstrated to have played a particular role in this trial as they held the preform shape, and did not allow it to sink into the channel spaces as would happen to a conventional preform. Thus, paradoxically, pre-consolidation worked in favour of the infusion time by allowing larger channels and faster resin delivery.

A CT scan of the pinned and infused preform, Figure 10, demonstrates several important aspects of both the pre-consolidation and the infusion procedures:

- (1) Thickness variation seen in the dry panel was largely preserved after infusion reaching ~20% difference between the infused and pinned areas. This clearly demonstrates the difference between high consolidation (rigid mould RTM or autoclave) and flexible bagging processes.
- (2) There was no impregnation defects formed around the pins, which suggests that in the presence of through-thickness flow the solid pins by themselves did not present a major obstacle

for impregnation. No clear boundary of any sort could be detected at the interface between the injected and the infused volumes, and pins were uniformly enveloped by the infused resin.

5. Discussion

5.1 Pin quality

The internal impregnation quality of pins depends on a balance of multiple parameters. The classical theory of RTM processes relates injection speed, and the properties of the resin and the resin-fibre interface, to the porosity volume fraction and the pore size [12-14]. In the resin printing process there is a significant number of other parameters which may have a direct impact on impregnation quality. This includes fabric constraints (fibre volume fraction at injection), injection volume, needle tapering size, needle diameter, the number of injections through-thickness, the time to maintain the needle in place after the injection (allowing inertial flow of the viscous resin), etc. Proper optimisation of the injection program requires a sophisticated analysis of the flow at the micro level in the vicinity of a tapered needle. Such a study goes beyond the scope of the current paper and requires further investigation. For the purposes of the current study – aimed at the feasibility of pre-consolidation – it was deemed sufficient to set the injection to minimise the inter yarn porosity (in the scale of millimetres) and accept the presence of intra-yarn micro-porosity (characteristic pore size of $\sim 10\text{ }\mu\text{m}$), which is less critical for key material properties such as inter-laminar strength and fracture toughness. Based on optical analysis (volume fraction of black pixels on a black and white representation of the cross-section image) the level of porosity within the pins was estimated to be below 2.5%.

A typical morphology of a first pre-consolidated and then infused sample is shown in Figure 10. Although no clear boundary between the injected and infused resin is seen, the area of injection could be recognised by pronounced micro-porosity which allows identifying the approximate boundaries of the pins. Even though the injections were spaced at equal distances (7 injections through thickness), the injected area formed a non-uniform cone with the boundaries not

coinciding with the volume of high compaction. A characteristic difference in yarn crimp is also seen for the yarns of different plies: the through-thickness span of yarn walk differs by 60% for the yarns at opposite surfaces. This reflects the thickness variation due to the elastic spring back of the preform after consolidation.

Thus the process of pre-consolidation creates an additional length scale, revealed in the variation of thickness and fibre volume fraction, regular interfaces between infused and injected resin, additional period of yarn waviness, and the non-uniformity of the ply geometry through thickness. The role of these features in mechanical behaviour, and damage accumulation mechanisms in particular, is yet to be understood. However, it is already clear that the added length scale increases the palette of available manufacturing parameters that can modify the material performance and tailor it to specific design needs.

5.2 Preform quality

The most promising aspect of resin pinning is the ability to control composite dimensions in critical locations (e.g. corners, junctions, fittings) where the thickness may have an impact on structural performance, where tolerance on dimensions is low, or where insufficient consolidation may lead to impregnation defects. For example, Hubert and Poursartip [27] have demonstrated that depending on the bagging conditions (presence or absence of a bleeder) laminates consolidated over a corner exhibit different flow and deformation mechanisms, which leads to dramatic difference in thicknesses and defect modes. Local stiffening of assembled or net-shape preforms guarantees that the preform remains stable in the course of infusion, debulking, and curing. This is also attractive for dry non-binded net-shaped preforms, where handling operations impact on its compressibility. The stability of preform can considerably simplify the manufacturing arrangements and so mitigate the probability of defect occurrence.

In less critical areas, a controlled thickness variation may be deemed acceptable, and even yield benefits in structural performance. Pinning of orthogonal woven preforms creates thickness variation if the pins are consolidated to a minimum achievable thickness that cannot be readily

reached using conventional flexible bagging processes. In this case local point-wise consolidation leads to a characteristic wavy surface of the preform and the resultant composite. If considered undesirable, this feature can be tackled or eliminated by adjusting the pin pattern and bridging the pins with non-crimp yarns.

Pre-consolidation used in pinning can increase the density of the preforms significantly, lowering permeability, but the infusion experiments showed that the preforms still remained infusable. Moreover, pinning provides a perspective method for controlling flow in the infusion process. It was shown that the pin pattern can direct the flow in a required (e.g. through-thickness or bias) direction, which may improve the reliability in a liquid moulding. In addition, the stiffness of skeletonised preforms allows for a greater flexibility in perfecting the manufacturing process. For instance, the resin delivery can be optimised by introducing resin channels without impacting on internal geometry of the material.

5.3 Processing perspectives

In its current form the pinning method considerably increases processing time as the material undergoes two curing procedures: once for resin pinning and the other time for the bulk of the matrix. These operations however can be optimised if, for example, fast curing thermoset resins or low-viscosity thermoplastic systems are used as the pin material. Fast solidification of pins would also imply that no heavy consolidation equipment is needed. Pins could be consolidated one by one applying low force but generating high pressure (for instance, a 10 kg force would only be required to generate excessive pressure on the 10 mm diameter pin). In this study, as it targeted the proof of concept only, the resin pins were consolidated all at once using a small hot press. However in industrial practice a compact tooling may be used for this purpose.

6. Conclusions

A novel binding concept was investigated and proven feasible. In contrast to conventional binding concepts, the novel method was implemented through the 3D printing of liquid resin

1 into dry reinforcements. The proof of concept was presented for one preform type, however the
2 developed approach is applicable to other textile reinforcement including 3D braided preforms.
3

4 The rig developed for this work demonstrates the potential of the concept. It allows for the
5 precise delivery of a liquid resin into a bulk textile preform through local, point-wise, and
6 highly controlled injections with a pattern that can be tailored to the requirements of infusion,
7 draping, or tuning of composite properties. A procedure for integrating binder through thickness
8 and creating pins was developed and implemented, and it was shown that pins, ribs, and other
9 forms of a stiff skeleton in a dry reinforcement can be printed in compliance with manufacturing
10 needs.
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21 The next stage of development in resin pinning involves perfecting the pins quality. Due to the
22 dual scale of fibre free space in preforms, the contrast of longitudinal and transverse yarn
23 permeabilities, and the action of intra-yarn capillary forces, the non-uniform unsaturated flow
24 leads to pore entrapment. The current injection procedure was set to minimise the intra-yarn
25 porosity, with the characteristic size exceeding one millimetre. Micro-porosity remained an
26 issue and needs to be tackled by multi-parametric optimisation procedures, which considers the
27 physical properties of resins and interfaces, the internal geometry of a preform, and the setting
28 of the injection printer. The advantage of the liquid printer is that it allows for exquisite control
29 of all the injection parameters. In particular, injection speed and hence the gradient of resin
30 pressure around the needle, can be set and adjusted to tune the pinning procedure for a particular
31 preform.
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46 It has been demonstrated that a new paradigm to additive manufacturing can be applied in the
47 context of liquid moulding and textile composite processing. The approach promises new
48 possibilities in controlling a preforms internal architecture, and component dimensions in
49 critical locations. Skeletonising textile preforms found to be effective for defect mitigation and
50 processing control. Though many issues are still to be addressed, the process suggests a new
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avenue to approach high quality rigid mould solutions for simplicity and cost of flexible moulding processes.

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8. References

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- 1 Ivanov D.S., Lomov S.V. Compaction behaviour of dense sheared woven preforms: experimental observations and Analytical predictions, *Composites Part A*, 64: 167-176, 2014.
 - 2 Mahadik Y., Scrimshaw C., Ward C., Ivanov D.S., Compressibility of complex 3D braided architectures, *Proceedings of TexComp conference*, Leuven, 16-20 Sept 2013.
 - 3 Rohatgi V., Lee J. Moldability of Tackified Fiber Preforms in Liquid Composite Molding, *Polymer Composites* 31 (7): 720–744, 1997
 - 4 Shih C. H., Lee L. Tackification of Textile Fiber Preforms in Resin Transfer Molding. *Journal of Composite Materials*, 35 (21): 1954–1981, 2001.
 - 5 Brody J.C., Gillespie J.W., Reactive and Non-reactive Binders in Glass/Vinyl Ester Composites, *Polymer Composites*, 26(3): 377-387, 2005.
 - 6 Wu W., Xie L., Jiang B., Ziegmann G. Simultaneous binding and toughening concept for textile reinforced pCBT composites: Manufacturing and flexural properties, *Composite Structures* 105: 279–287, 2013
 - 7 Tsotsis K.T., Method and apparatus for melt-bonded materials for tackification of dry fabric preforms, US 2005/0257887 A1.
 - 8 Hogg P.J., Toughening of thermosetting composites with thermoplastic fibres, *Materials Science and Engineering A* 412: 97–103, 2005.
 - 9 Abusafieh A.R.B., Doyle M., Lo Faro C., Maskell R., Price R. Process and performance enhancements in resin infusion using an epoxy-soluble non-woven veil, *SAMPE International Conference 2006*, Paris.
 - 10 Beier U. et al. , Mechanical performance of carbon fibre-reinforced composites based on preforms stitched with innovative low-melting temperature and matrix soluble thermoplastic yarns, *Composites: Part A* 39 (2008) 1572–1581
 - 11 Thoma B., Weidenmann K.A., Henning F. Chemical-stitching, ein vielversprechender Ansatz für die automatisierte Preform-Fertigung, *Journal of Plastics Technology*, 8: 2012, 491-514.

- 12 Patel N., Rohatgi V., Lee L.J. Microscale flow behavior and void formation mechanism during impregnation through a unidirectional stitched fiberglass mat. *Polym Eng Sci*, 35(10):837–51, 1995.
- 13 Gourichon B., Binetruy C., Krawczak P. Experimental investigation of high fiber tow count fabric unsaturation during RTM, *Composites Science and Technology* 66 (2006) 976–982
- 14 Leclerc J.S., Ruiz E. Porosity reduction using optimized flow velocity in Resin Transfer Molding, *Composites: Part A* 39: 1859–1868, 2008.
- 15 Brusckie M.V., Advani S.G. Flow of generalized Newtonian fluids across a periodic array of cylinders. *Journal of Rheology*, 37(3):479–496, 1993.
- 16 Gebart B.R.. Permeability of unidirectional reinforcements for RTM, *Journal of Composite Materials*, 26(8):1100–1133, 1992.
- 17 Sadiq T.A.K., Advani S.G., Parnas R.S.. Experimental investigation of transverse flow through aligned cylinders. *International Journal of Multiphase flow*, 21(5):755–774, 1995.
- 18 Grouve W.J.B., Akkerman R., Loendersloot R., van den Berg S. Transverse permeability of woven fabrics, *Int J Mater Form*, 1:859–862, 2008
- 19 Alms J.B., Advani S.G., Glancey J.L. Liquid Composite Molding control methodologies using Vacuum Induced Preform Relaxation, *Composites: Part A* 42: 57–65, 2011.
- 20 Pearce N.R.L., Summerscales J., Guild F.J., Improving the resin transfer moulding process for fabric-reinforced composites by modification of the fabric architecture, *Composites: Part A* 31: 1433–1441, 2000.
- 21 Seemann W.H. US Patent 4, 902, 215; 1990.
- 22 Bickerton S., Advani S.G., Mohan R.V., Shires D.R. Experimental analysis and numerical modeling of flow channel effects in resin transfer molding. *Polym Compos*, 21: 134–53, 2000.
- 23 Dai J., Pellaton D., Hahn H.T. A comparative study of Vacuum-Assisted Resin Transfer Molding (VARTM) for sandwich panels. *Polym Compos*, 24(6):672–85, 2003.
- 24 Allende M., Mohan R.V., Walsh S.M. Experimental and numerical analysis of flow behavior in the FASTRAC liquid composite manufacturing process, *Polym Compos*, 25(4):384–96, 2004.
- 25 Markicevic B, Litchfield D, Heider D, Walsh S, Advani SG. Role of flow enhancement network during filling of fibrous porous media. *J Porous Media*, 8(3):281–97, 2005.
- 26 Alms J.B., Advani S.G., Simulation and experimental validation of flow flooding chamber method of resin delivery in liquid composite molding, *Composites: Part A* 38, 2131–2141, 2007.
- 27 Hubert P., Poursartip A. Aspects of the compaction of composite angle laminates: an experimental investigation, *J of Composite Materials*, 35(2001): 2-26.

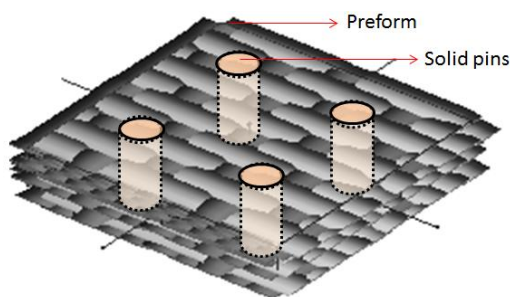


Figure 1. Sketch illustrating the idea of resin pinning: solid cured pins spanning through the thickness of dry multi-ply preform

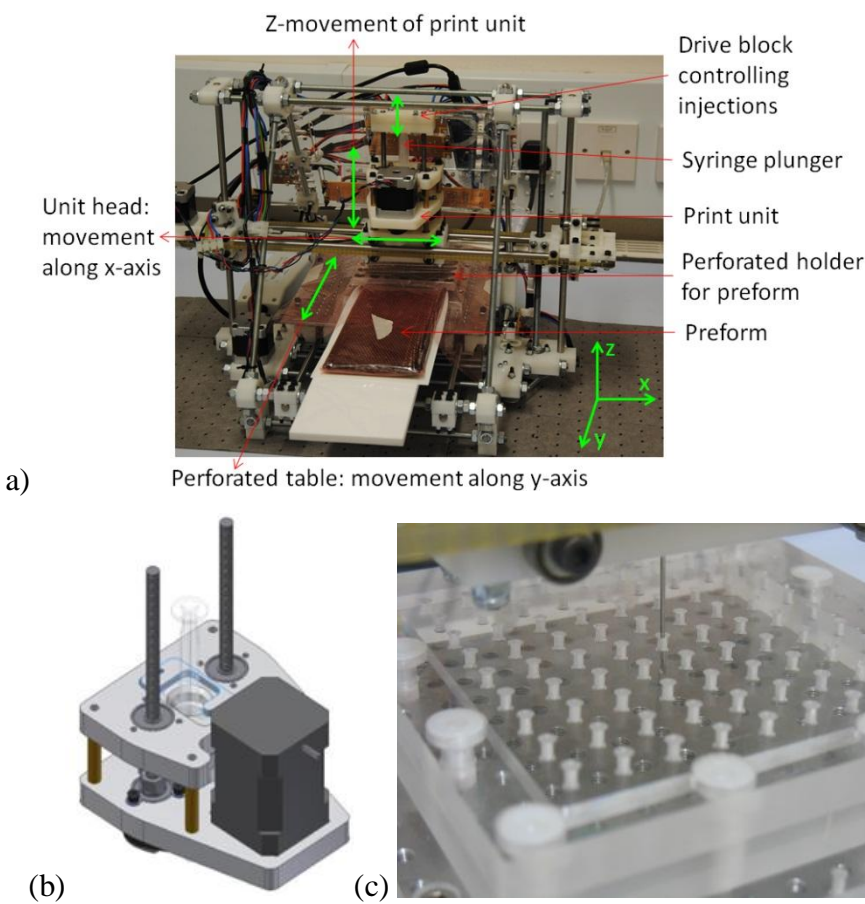


Figure 2 (a) Modified rapid prototyping RepRap rig, (b) schematic of printing unit on the rig with the preform constraining rig mounted on the bed rig, (c) needle injecting resin through the holes into the perforated preform holder.

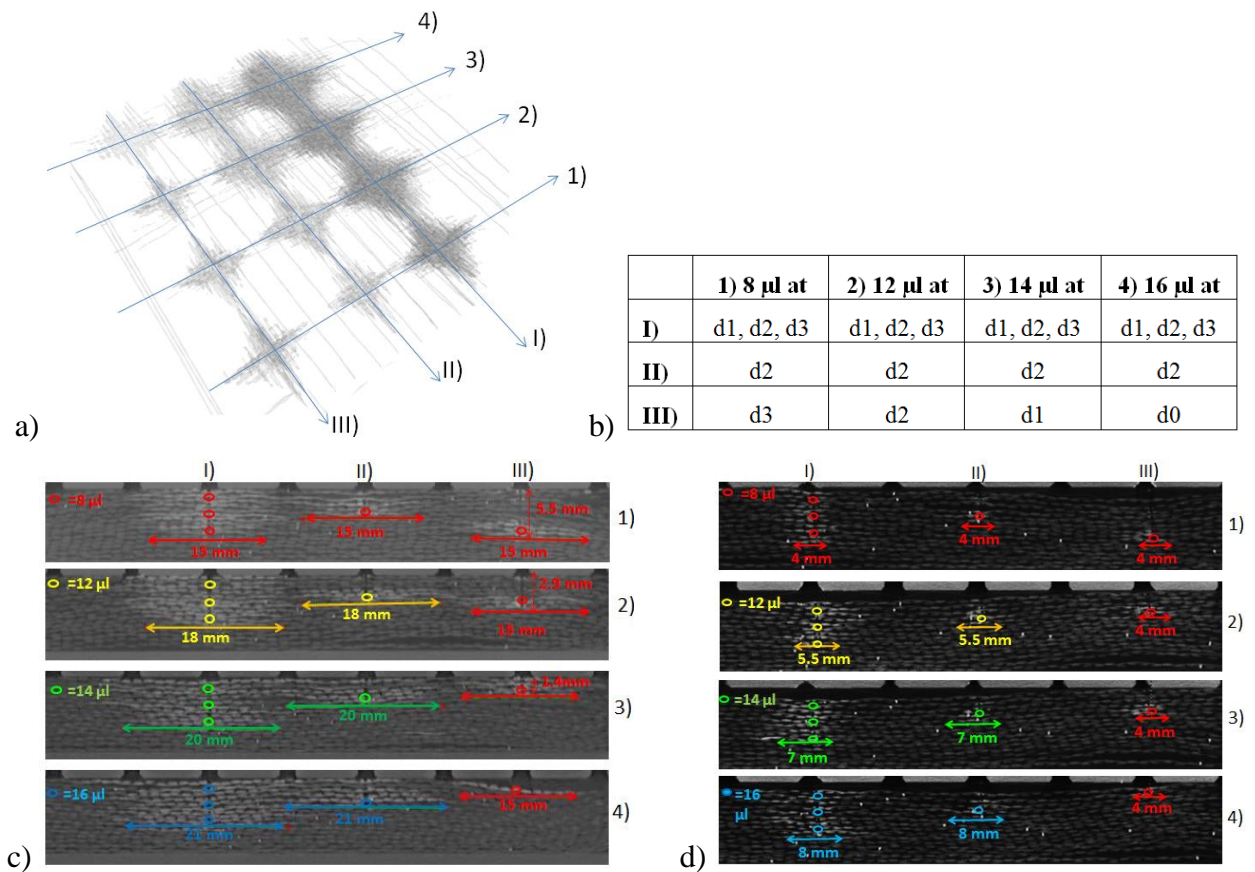


Figure 3. CT-Scan of Zn solutions injected into a woven carbon fabric (a) general view of traces left by propanol solution (seen as dark area), (b) the summary of depths at which injections are made ($d_3 = 5.5$ mm, $d_2 = 2.9$ mm, $d_1 = 1.4$ mm, $d_0 = 0.1$ mm), (c) Zn traces of propanol based solution (seen as white on dark preform) and (d) Tracers of epoxy based solution. The locations of injections are shown by circles (red – 8 μ l, yellow – 12 μ l, green – 14 μ l, blue – 16 μ l).

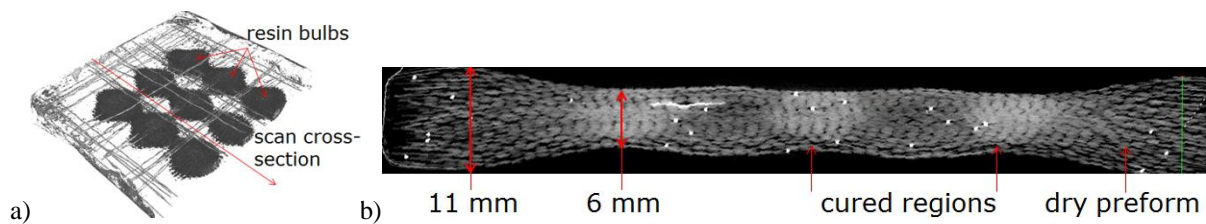


Figure 4. CT-scans of consolidated preform with 40 μ l volume per injection: a) cured zones and b) cross-section between the cured zones showing the thickness variation

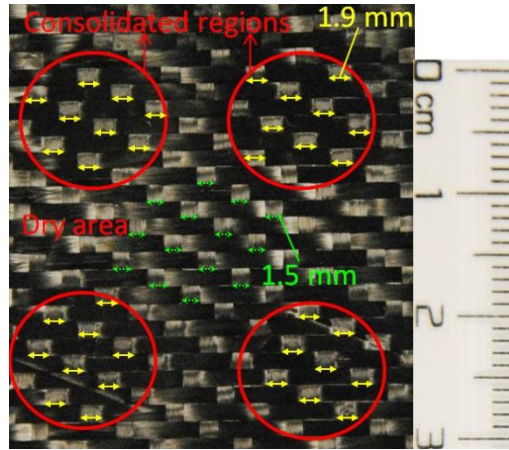


Figure 5. In-plane geometry of consolidated fabric. The characteristic yarn width is marked with solid yellow lines in the consolidated region (all arrows are 1.9 mm) and by green dot lines in the dry area (all arrows are 1.5 mm).

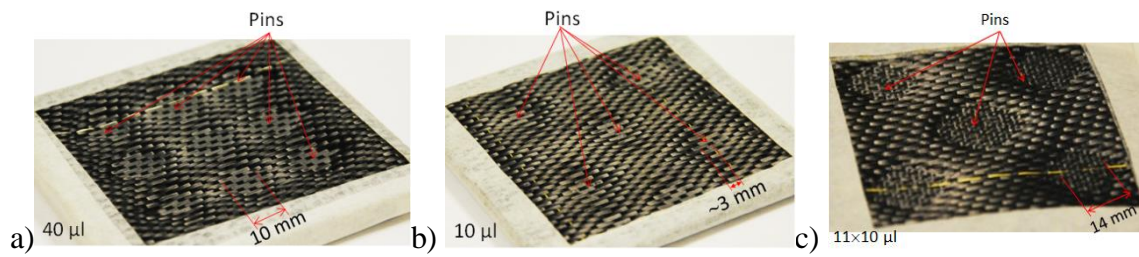


Figure 6. Consolidated 24-ply woven preforms (a) 0° laminate, seven $40\ \mu\text{l}$ injections per pin, 20 mm spacing; (b) 0° laminate, ten $10\ \mu\text{l}$ injections per pin, 28.3 mm spacing; (c) $(0^\circ/45^\circ)_s$, eleven $10\ \mu\text{l}$ injections per pin, 28.3 mm spacing.

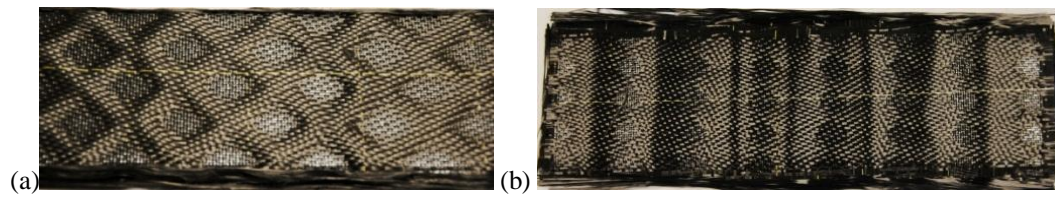


Figure 7. Examples of pre-consolidated panels (300×90 mm) of 24 ply 5HS preforms: (a) diagonal pattern, each pin is made by seven $20\ \mu\text{l}$ injection through the preform thickness, (b) rib pattern, each pin is made by ten $10\ \mu\text{l}$ injection through the preform thickness.

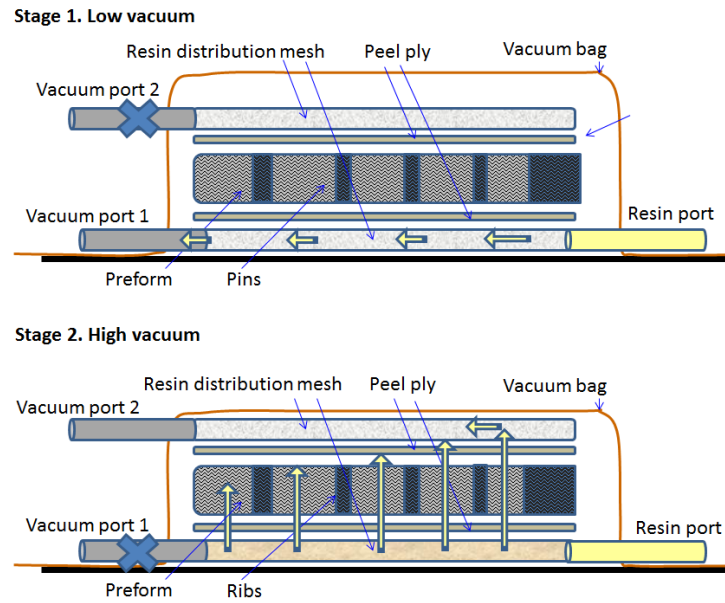


Figure 8. Two-stage infusion where stiff ribs across the panel cut the in-plane flow off and promote through-thickness flow only.

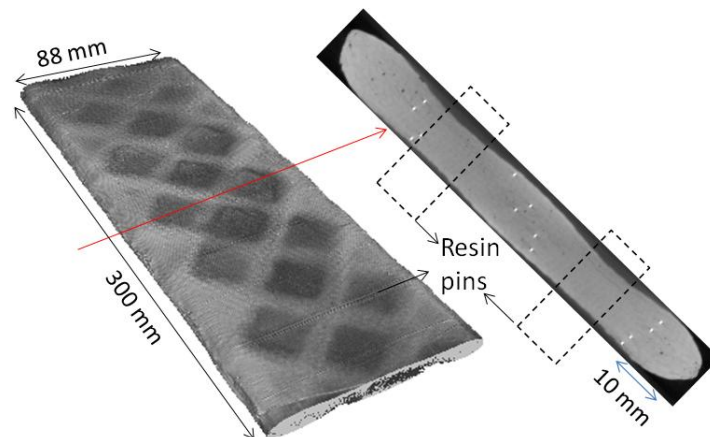


Figure 9. X-Ray tomography of the infused pre-consolidated panel (seven 20 μ l injections per thickness, 10 mm pin diameter): surface texture (on the left: dark area indicate valleys, grey area - hills) and the section across the panel length (on the right). NB: white spots are the polyester trace yarns inserted in the carbon preform.

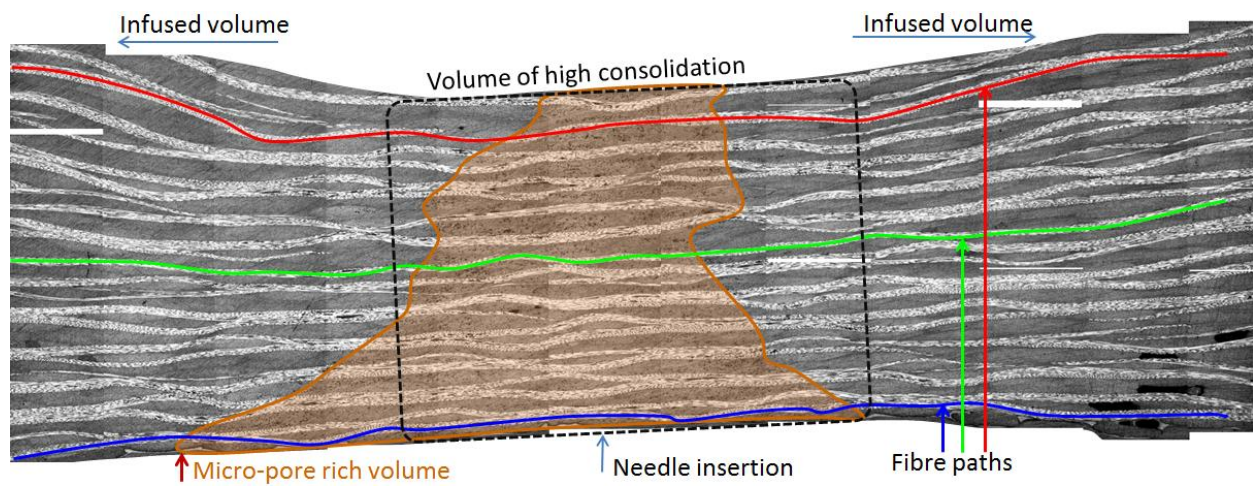


Figure 10. Cross-section of the resin pinned and infused composite in the vicinity of injection (non-optimised injection parameters). The through-thickness spans of highlighted yarns at the upper surface and in the centre are 60% and 35% higher than the one at the bottom.